Characterization of the Lunar Regolith: Everything You Ever Wanted to Know about the Lunar Regolith with Lessons from Apollo

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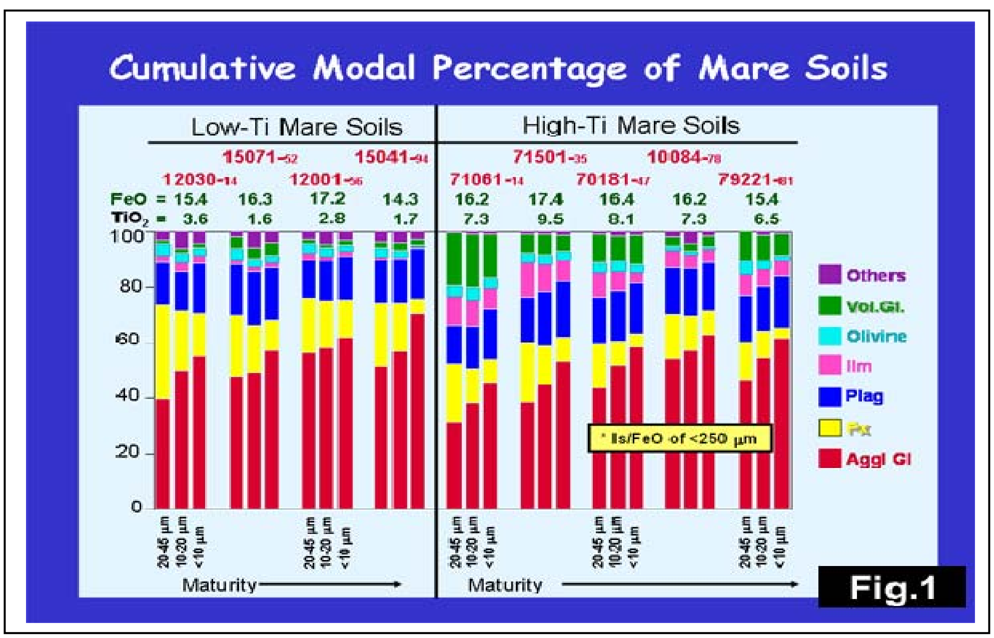
Formation of Lunar Soil: The lunar soil formed by space weathering processes, the most important of which is micrometeorite (< 1mm) impact dynamics. Although of small mass, these particles possess large amounts of kinetic energy, impinging on the lunar surface with velocities up to 100,000 km/hr. Much of the impacting energy goes into breaking and crushing of fragments into smaller pieces; however, due to the high energy of many of the impacts, the lunar soil is partially to completely melted on a local scale of millimeters. The melted soil incorporates soil fragments and quenches to glass. These aggregates of minerals, rocklets, and glasses are welded (i.e., cemented) together into "agglutinates" [1]. It is the glass in these fragile agglutinates that further becomes comminuted into smaller pieces making for ever-increasing amounts of glass to the lunar soils. Portions of these silicate melts also vaporize, only to condense upon the surfaces of all soil grains. Other cosmic, galactic, and solar-wind particles also perform minor weathering, largely by sputtering; but many of these particles remain imbedded in the outer portions of all lunar soil grains. As demonstrated by Taylor & McKay [2], as the number of lithic fragments decreases, the amount of liberated free minerals increases to a point, with continuing exposure to impact processes actually decreasing the abundance of these mineral fragments. With these changes in rock and mineral fragments, the major accompanying process is the formation of the glass-welded agglutinates; and the abundances of agglutinitic glass increase significantly with decreasing grain size (Fig. 1, [3]), as well as increase in maturity of the soil. Due to complicated interactions of the impact melts with solar-wind, as well as productions of vaporized chemistry, the glass of the lunar soil contains myriads of nano-sized Fe^0 grains (4-33 nm), with the soil containing 10X more Fe^0 than the rocks from



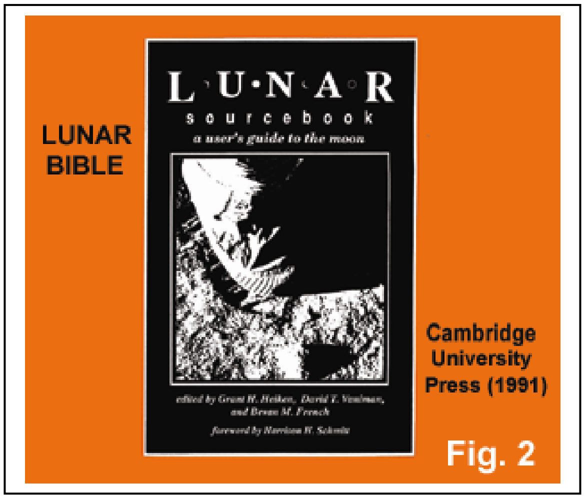


Fig. 2

which it was derived. As a result of all this space weathering, the resulting lunar soil consists of rocklets, minerals, and agglutinates, with major amounts of glasses, impact-produced but also volcanic in origin.

The abundances of glass in lunar soil increases with decreasing grain size, such that the "dust" (i.e., <50 µm) portion of the lunar soil contains over 50% glass [Fig. 1], present as sharp, abrasive, interlocking, fragile glass shards and fragments. It is this same "dust" at <50 µm that constitutes approximately 50% of mature lunar soils, as a rule-of-thumb for size distributions. It is the mainly the presence of these huge quantities of glass that contributes to the unusual engineering properties of lunar soil [4].

Geotechnical Soil Properties for Consideration

Figure 2 shows "The Lunar Bible" in which the geologic and engineering properties of lunar regolith are presented in detail, by 'lunatic' authorities. This should be the first stop in anyone's search for data about the rocks and soils of the Moon.

Figures 3 give some important geotechnical properties of lunar regolith culled from a chapter in the Lunar Sourcebook by Carrier et al. [5]. Data such as these must be used in any approach to ISRU of lunar materials.

References: **[1] McKay, D.S., and A. Basu, 1983**, The production curve for agglutinates in planetary regoliths. Jour. Geophys. Res. 88, B-193-199; **[2] Taylor, L.A., and D.S. McKay, 1992,** Beneficiation of lunar rocks and regolith: Concepts and difficulties. In Engineering, Construction, Operations in Space III, Vol. I, ASCE, New York, 1058-1069; **[3] Taylor, L.A., Pieters, C., Keller, L.P., Morris, R.V., McKay, D.S., 2001,** Lunar mare soils: Space weathering and the major effects of surface-correlated nanophase Fe. *Jour. Geophys. Lett. 106*, 27,985-27,999; **[4] Taylor, L.A., Pieters, C., Keller, L.P., Morris, R.V., and McKay, D.S., 2001,** The effects of space weathering on Apollo 17 mare soils: Petrographic and chemical characterization. . *Meteor. Planet. Sci. 36*, 285-299; **[5] Carrier, W.D., III, Olhoeft, G.R., and Mendell, W., 1991,** Physical properties of the lunar surface. in *Lunar Sourcebook*, ed. by G. Heiken, D. Vaniman, and B. French, Cambridge University Press, New York, 475-594**;**

Fig. 3. "One Simulant Does Not Fit All Needs"

	Chemistry	Geotech/ Engr	Simulant
Facilities Construction	X	XX	JSC-2
Regolith Digging and Moving		XX	JSC-2
Trafficability (e.g., Roads)		XX	JSC-2
Microwave Processing	XX	X	NP-1+JSC-2+MLS-2
Conventional Heat Treatment	X	X	JSC-2+MLS-2
Oxygen Production	X	X	JSC-2+MLS-1+MLS-2
Dust Abatement	X	X	NP-1+JSC-2
Mineral Beneficiation	X	X	???
Solar-Wind Gas Release	X	X	JSC-2+Ion Implant
Cement Manufacture	XX		MLS-1+MLS-2
Radiation Protection	X	X	JSC-2+MLS-1+MLS-2

Mare Soil:	**JSC-2**	= JSC-1 in chemistry + Geotech Prop.
	MLS-1	= Chemistry only of Apollo 11 soil (no glass)
Highland Soil:	**MLS-2**	= Anorthosite = Chemistry only
Magnetic Soil:	**NP-1**	= Magnetic properties only